Observational and Theoretical Review of the Multiphase ISM

So, it works in Practice…but does it work in Theory?

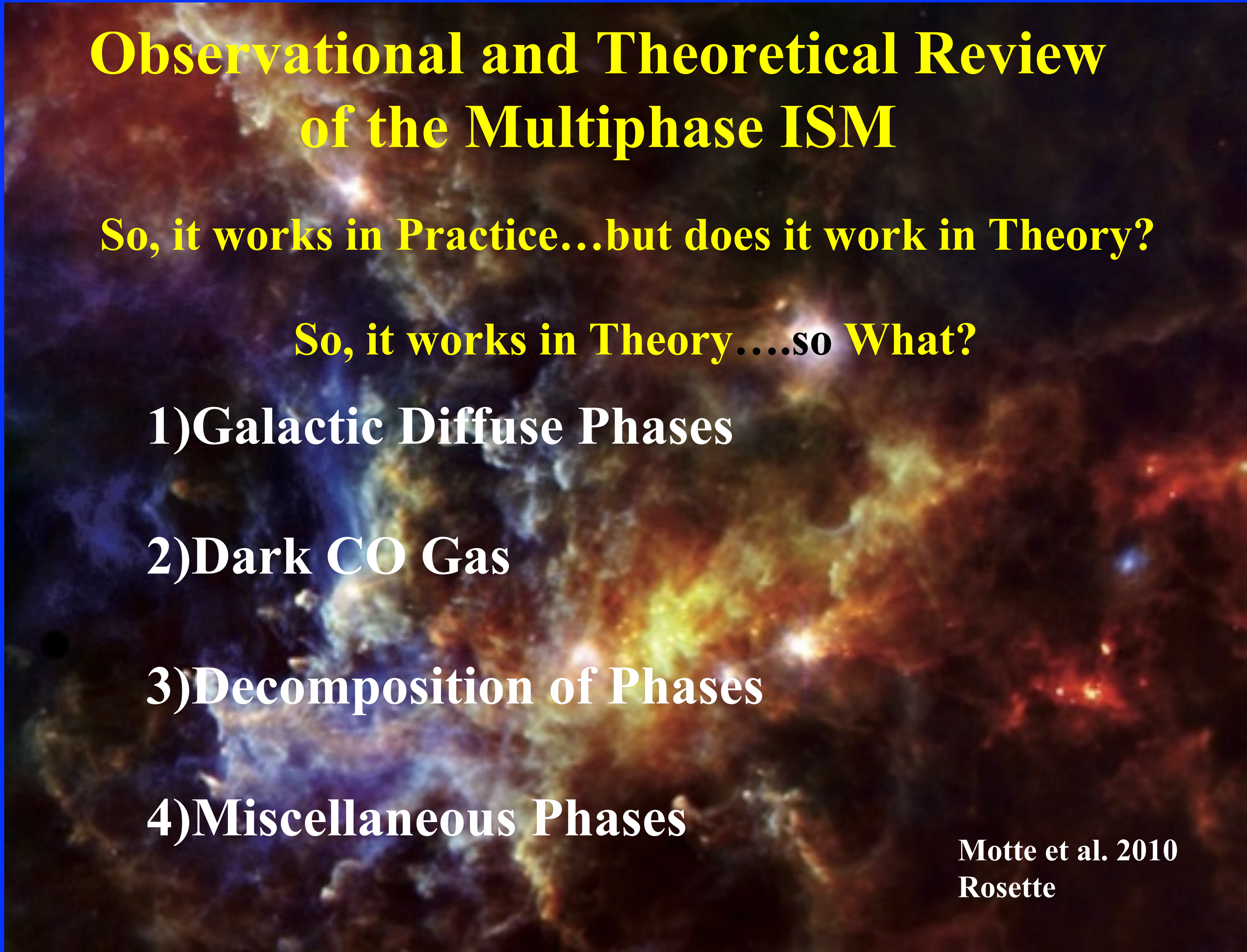
So, it works in Theory….so What?

1)Galactic Diffuse Phases

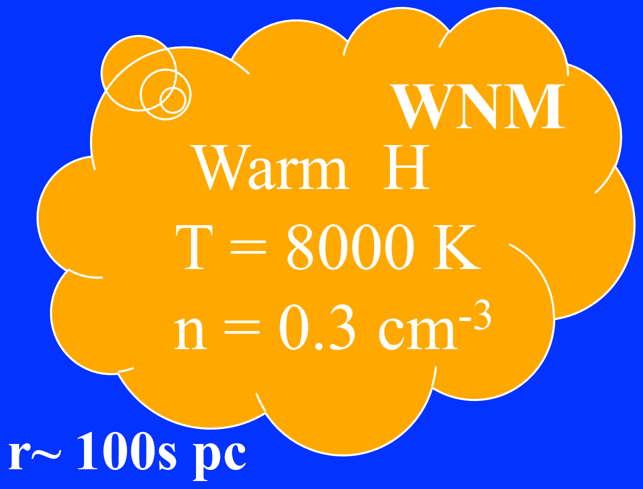
2)Dark CO Gas

3)Decomposition of Phases

4)Miscellaneous Phases



Motte et al. 2010
Rosette



PDR: Gas phase in which FUV radiation plays a role in the heating and/or chemistry

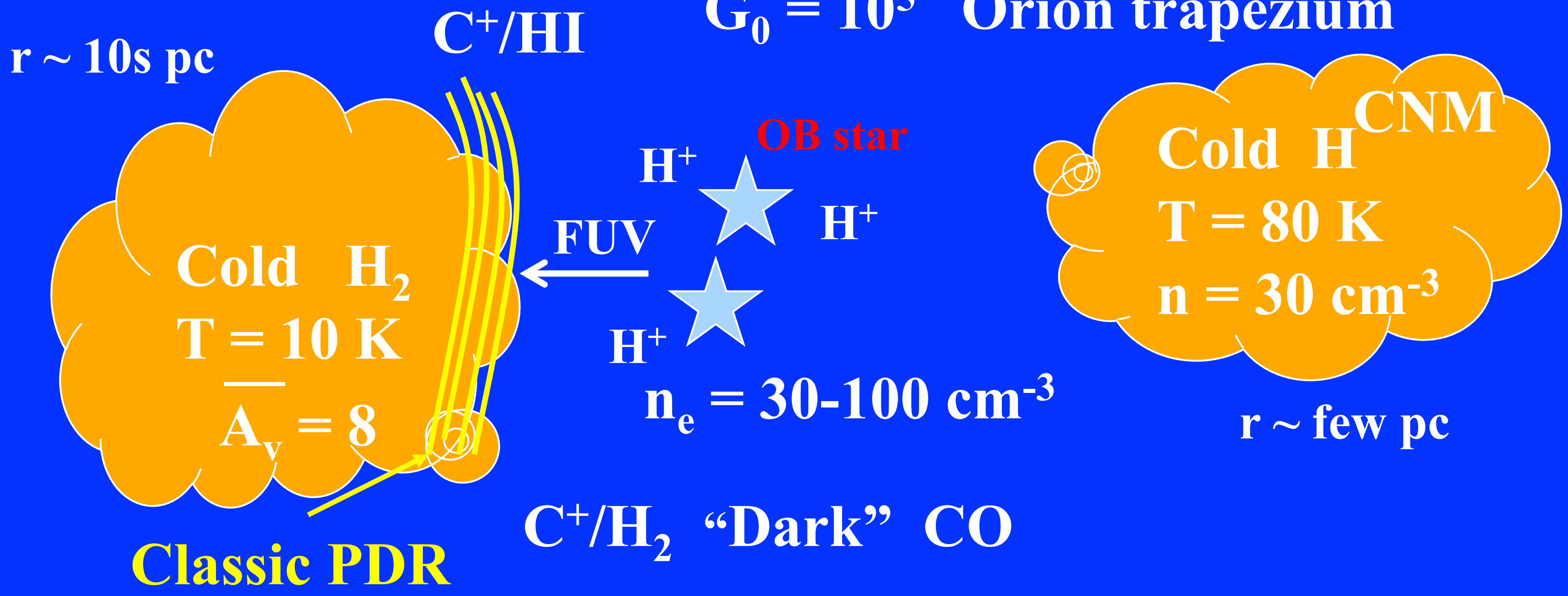
FUV: 6 eV – 13.6 eV

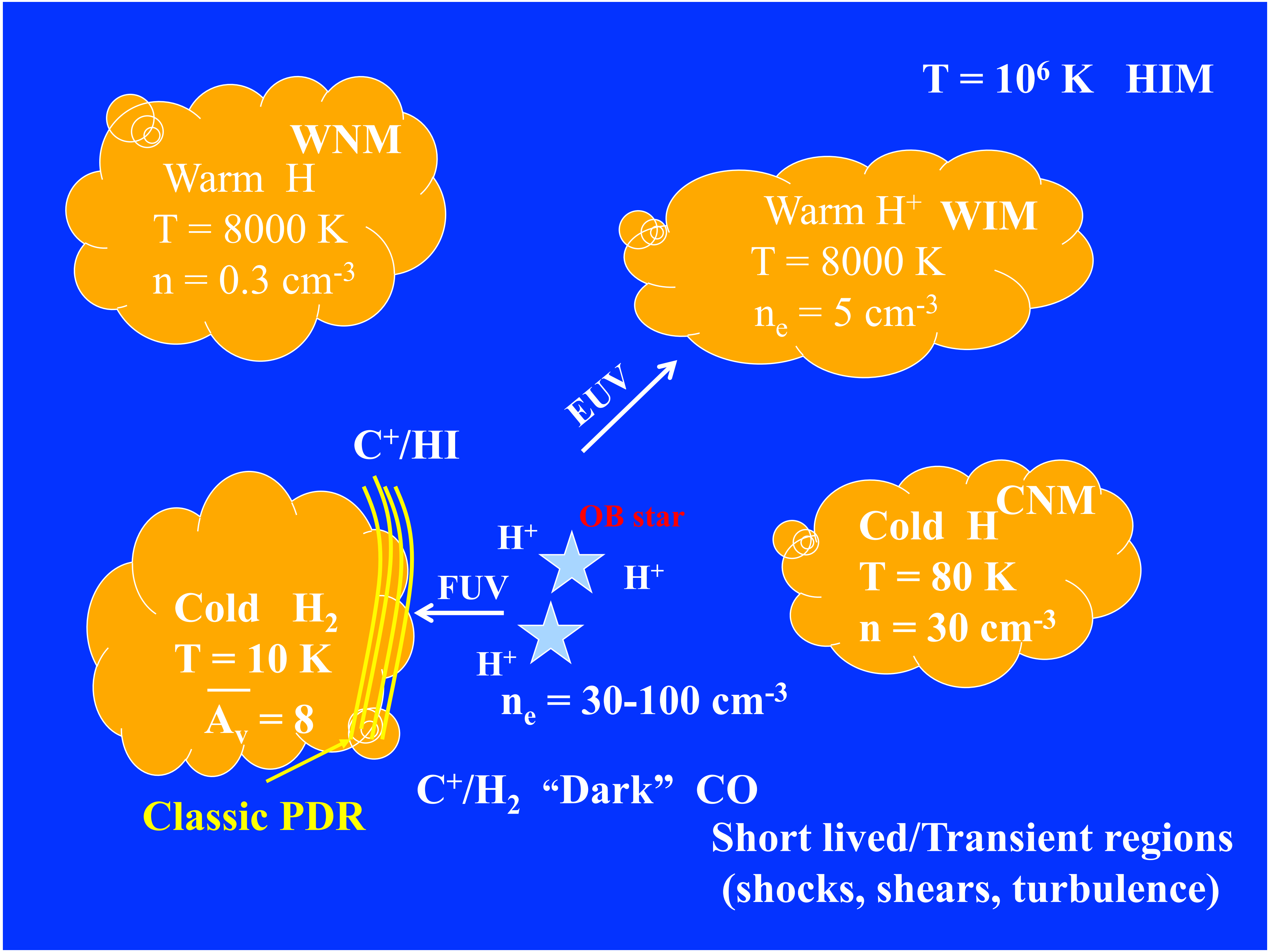
$G_0 = 1$ Interstellar field

G_0: Habing χ:Draine ~1.7 G_0

U: Mathis ~ 1.1G_0

$G_0 = 10^5$ Orion trapezium




T = 10^6 K HIM
WNM
Warm H
T = 8000 K
n = 0.3 cm^-3
Warm H^+ WIM
T = 8000 K
n_e = 5 cm^-3
EUV
C^+/HI
OB star
H^+
H^+
H^+
FUV
Cold H_2
T = 10 K
A_v = 8
CNM
Cold H
T = 80 K
n = 30 cm^-3
n_e = 30-100 cm^-3
Classic PDR
C^+/H_2 "Dark" CO
Short lived/Transient regions
(shocks, shears, turbulence)

Diffuse Gas Heating/Cooling

Ionization: FUV, X-ray, C.R.
Heating: P.E., C.R., X-ray/EUV
Cooling: [CII], [OI], Lyα,
e^- recombination

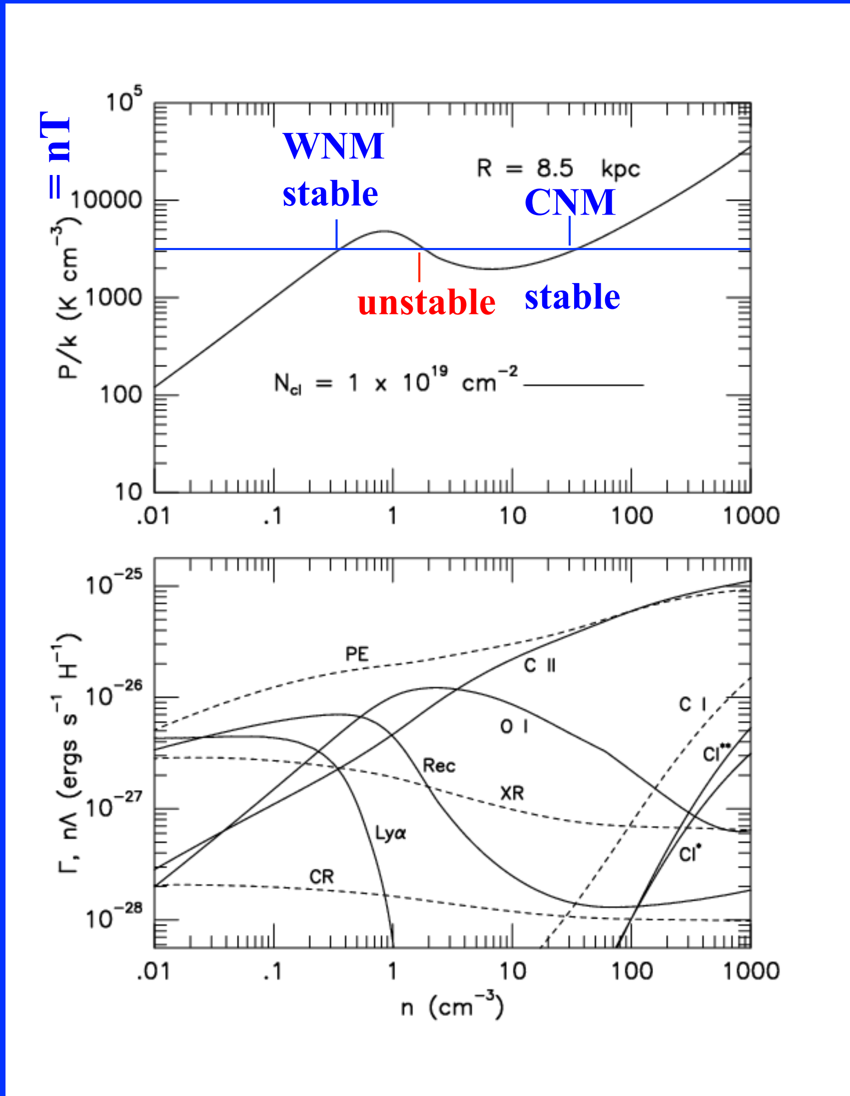
$$n\Gamma = n^2\Lambda$$

$$\downarrow$$

$$T$$

$T = 7860$ $n = 0.35\ cm^{-3}$
WNM

$T = 85$ $n = 33\ cm^{-3}$
CNM



Wolfire et al. (2003)

Diffuse Gas Heating/Cooling

C II Cooling/H (CNM) >
10 CII Cooling/H (WNM)

** Note **

CNM in Thermal Balance:
[CII] measures the total energy dumped into the gas.

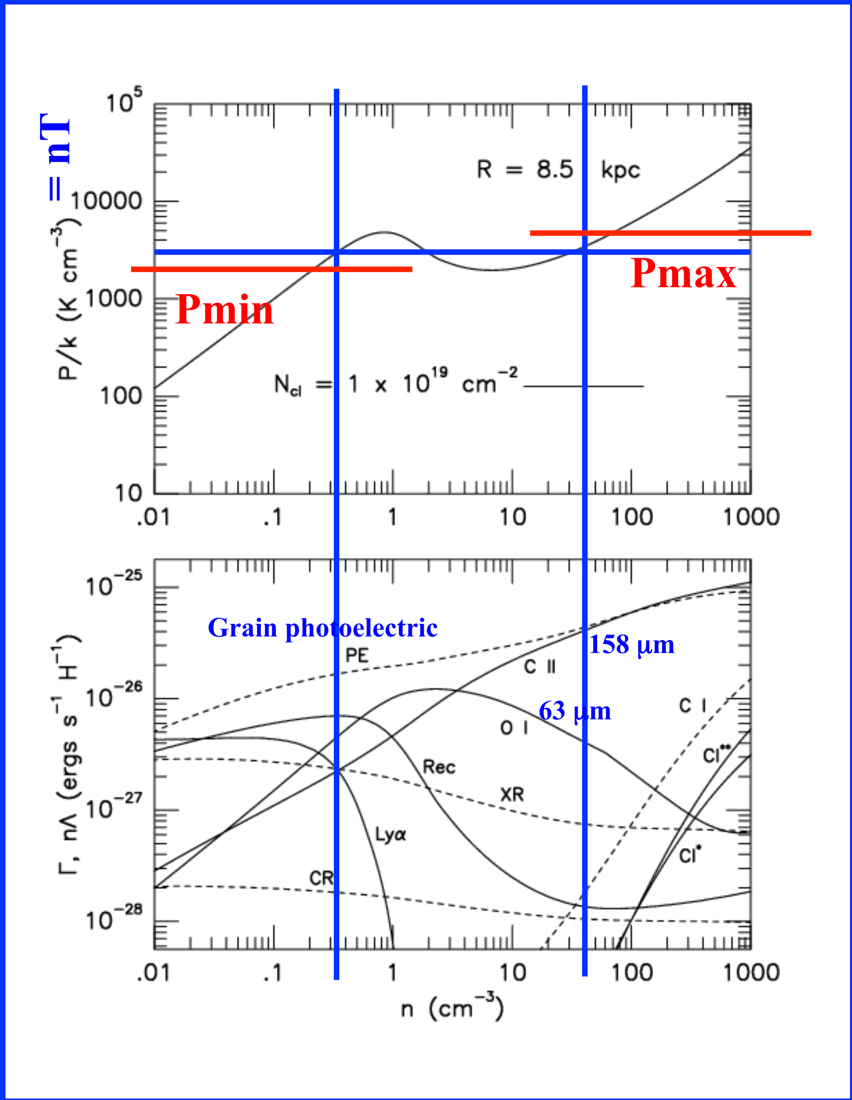
Heating Rate = const

n ↓

Z ↓

T ↑

[CII] = const



Wolfire et al. (2003)

C.R. ionization
Indriolo et al. 2012

Thermal Pressure
Jenkins et al. 2011

C II Cooling/H (CNM) >
10 CII Cooling/H (WNM)

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n ↓
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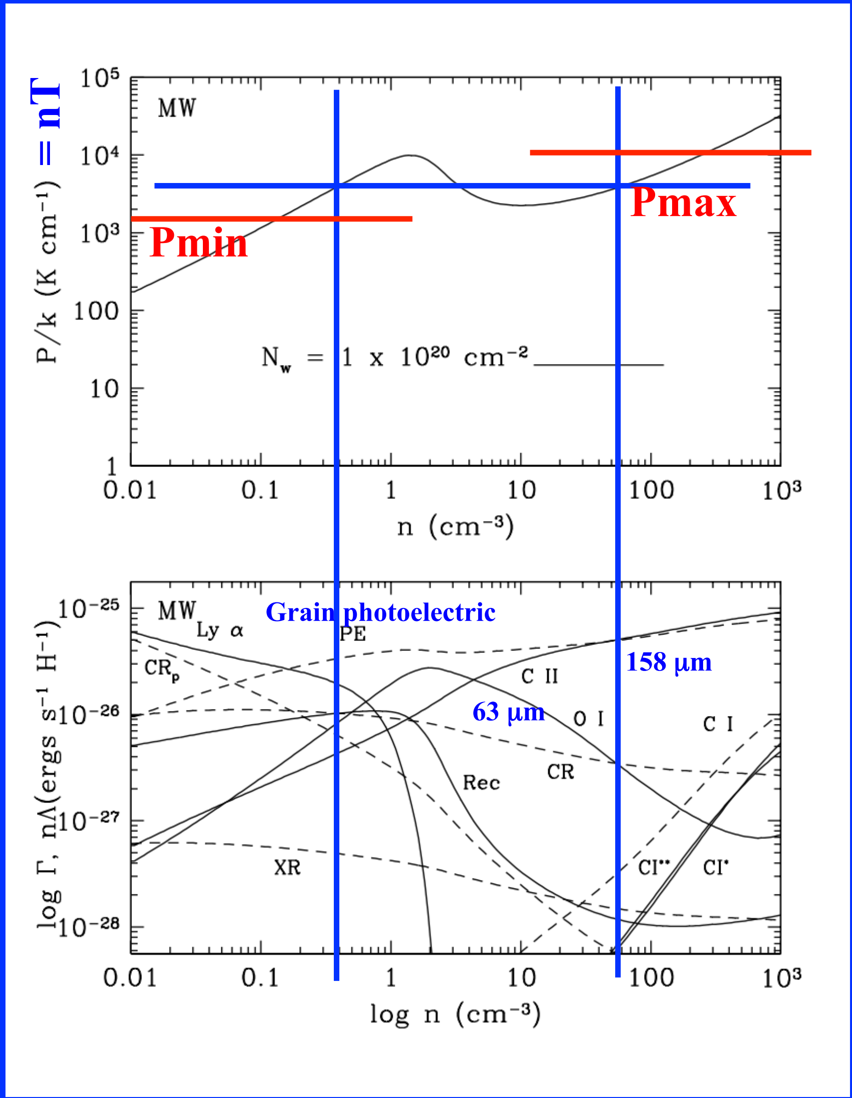
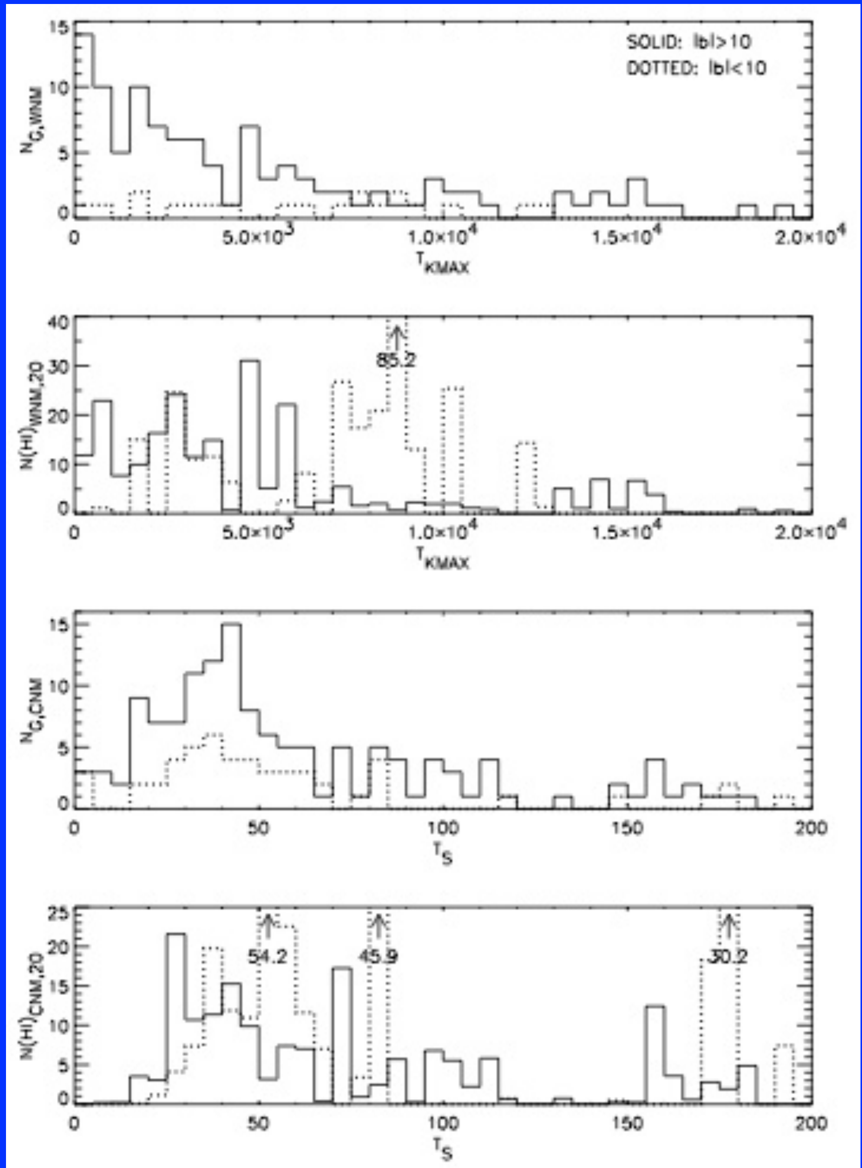
Diffuse Gas Heating/Cooling



Wolfire et al. (2013)



Heiles & Troland 2003, ApJ, 586, 1067
Begum et al. 2010

WNM temperature distribution

50% of gas mass in unstable Ts ???

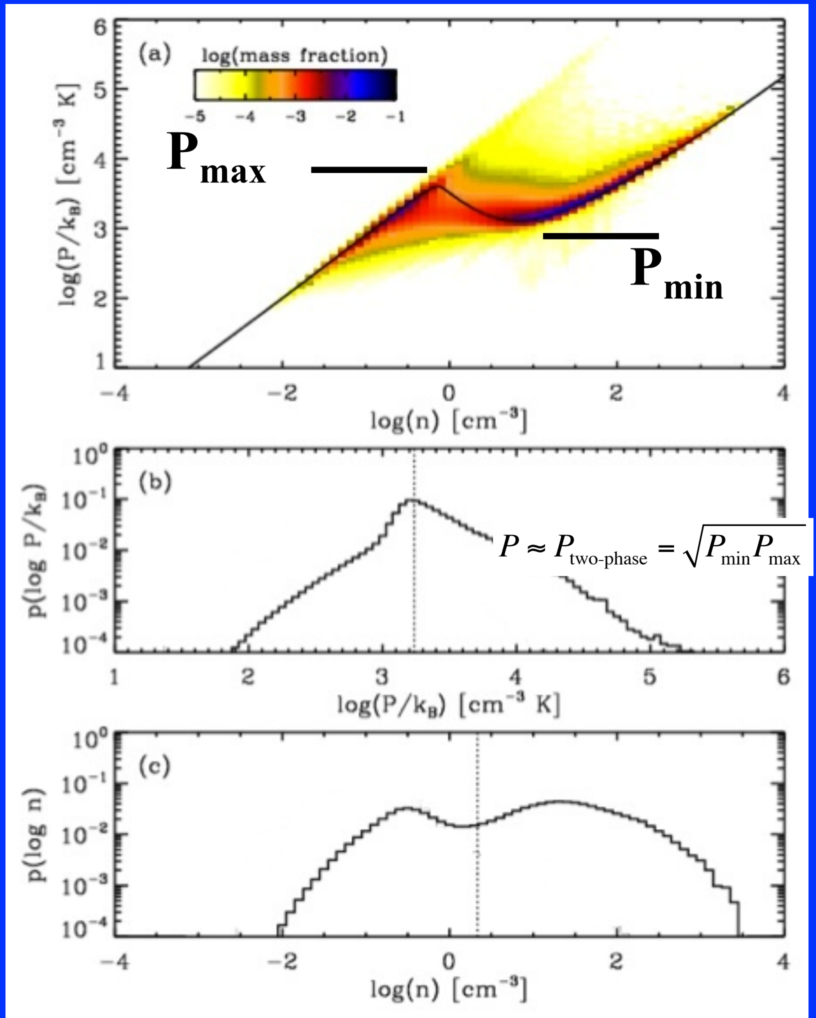
Locally: 60% WNM, 40% CNM (also Pineda et al. 2013)

In plane 25% of WNM in unstable Ts or 15% of total mass.

Out of plane dominated by dynamical processes.

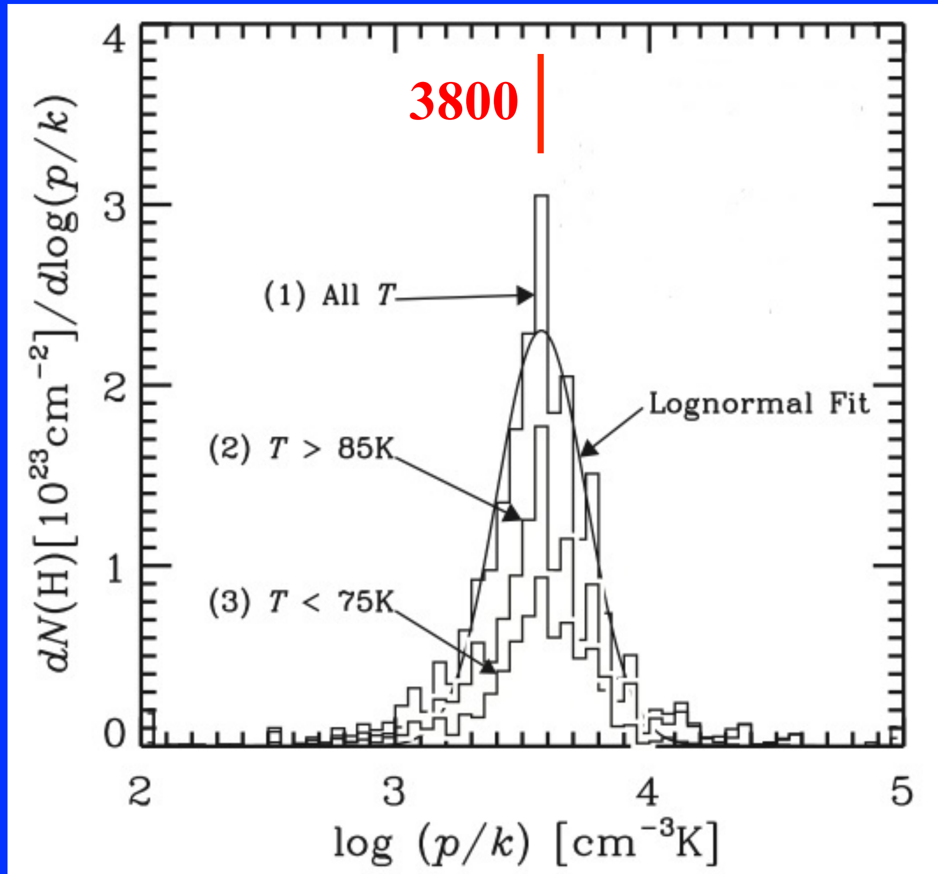
In plane uncertainties large, and statistics poor: 8 in 79 out

Multiphase Galactic Disks



Kim, Kim, & Ostriker 2011

Thermal Pressure in CNM



Jenkins & Tripp 2011

Regulation of Thermal Pressure

$$P_{\text{tot}} \propto \Sigma^2_{(\text{WNM})\ \text{gas}}$$

$$P_{\text{th}} = \alpha P_{\text{tot}}$$

$$\alpha \approx 10\% - 20\%$$

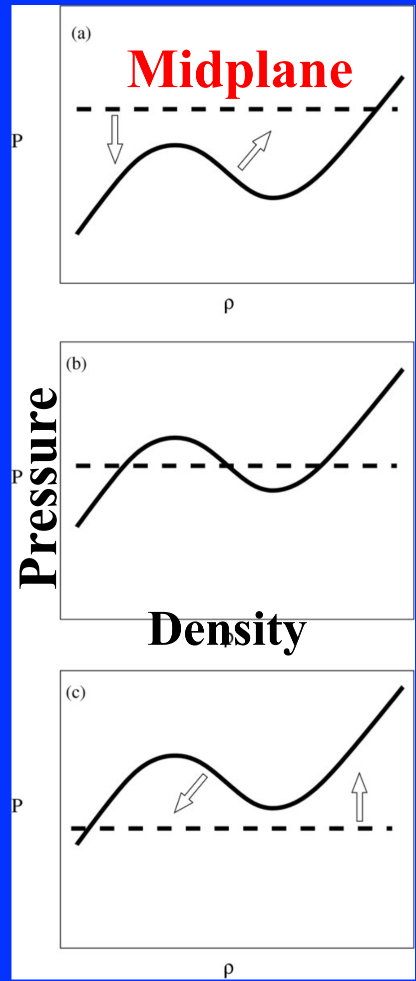
CNM / WNM are PDRs (heated by FUV)

More CNM leads to more star formation (FUV)

Too Warm

Just Right

Too Cold



Ostriker, McKee, & Leroy 2010

Molecular Hydrogen

$N_{tot} - N_{HI} - N_{CO} = N_{Dark\ Gas}$

IRAS 100 µm 30% DG
Planck IR 50% DG

EGRET γ rays 30% DG

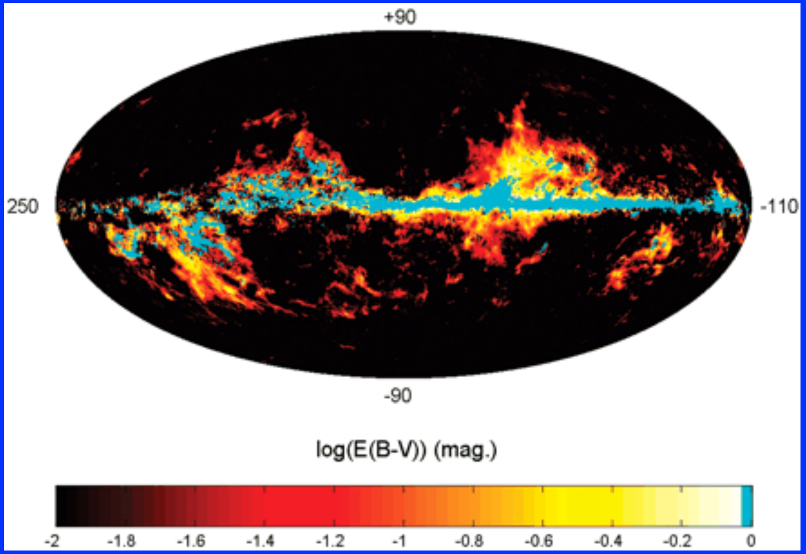
Fermi γ rays 50% DG

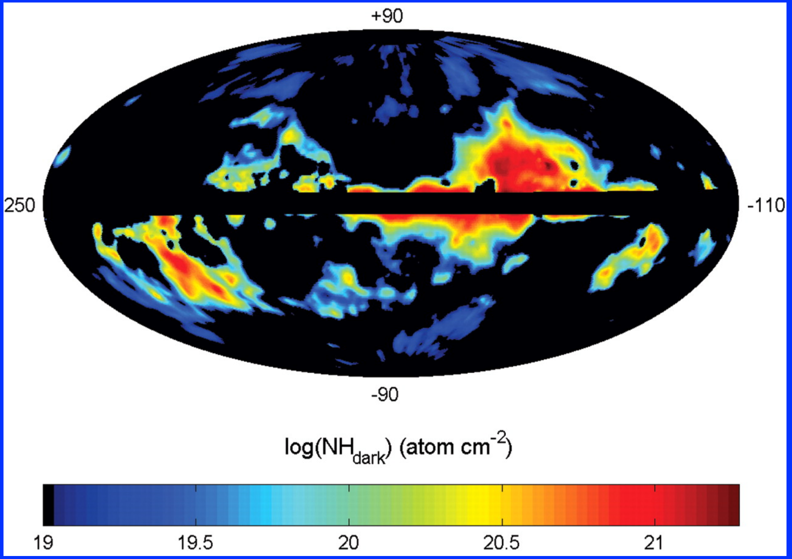
Extinction (2MASS) 43-71% DG

Herschel Got C^+ 30% DG

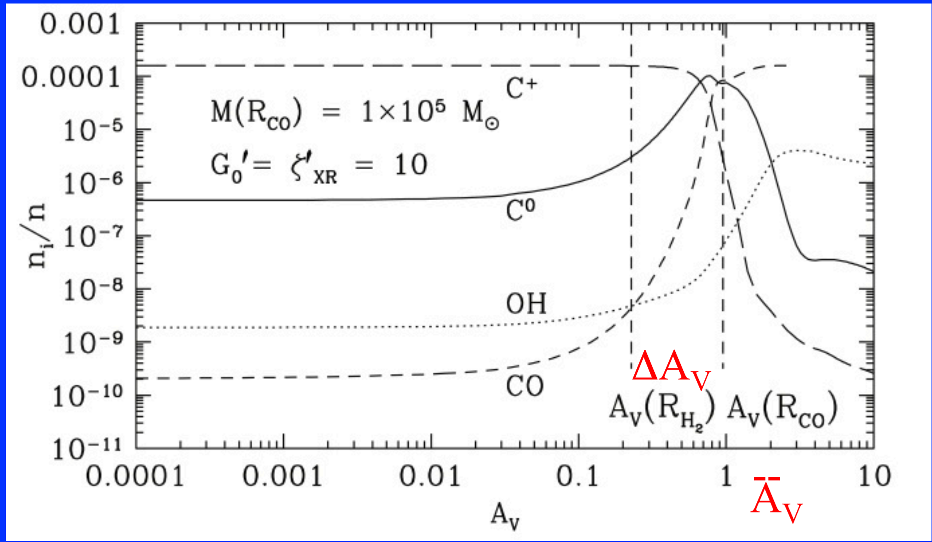
Dark Molecular Gas

C^+/H_2 but no CO





Grenier et al. 2005, Science, 307, 1292

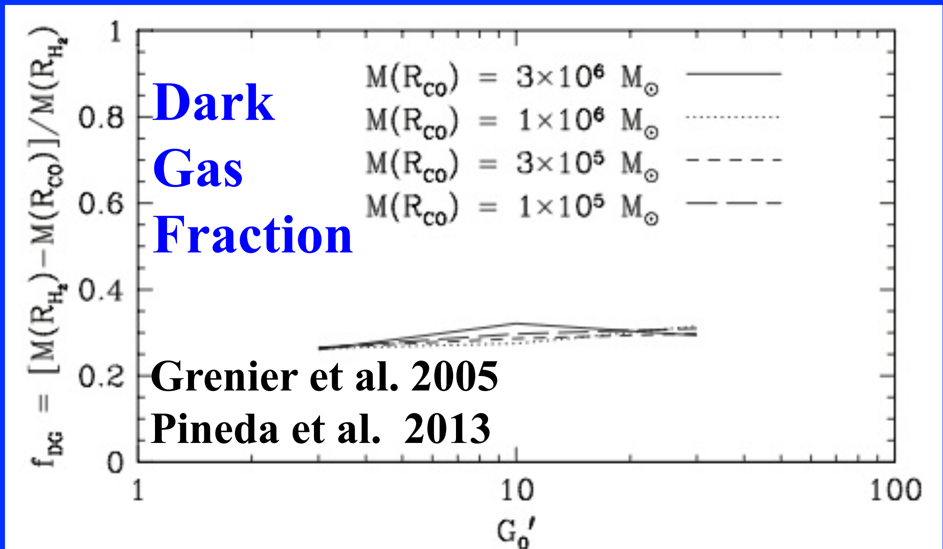


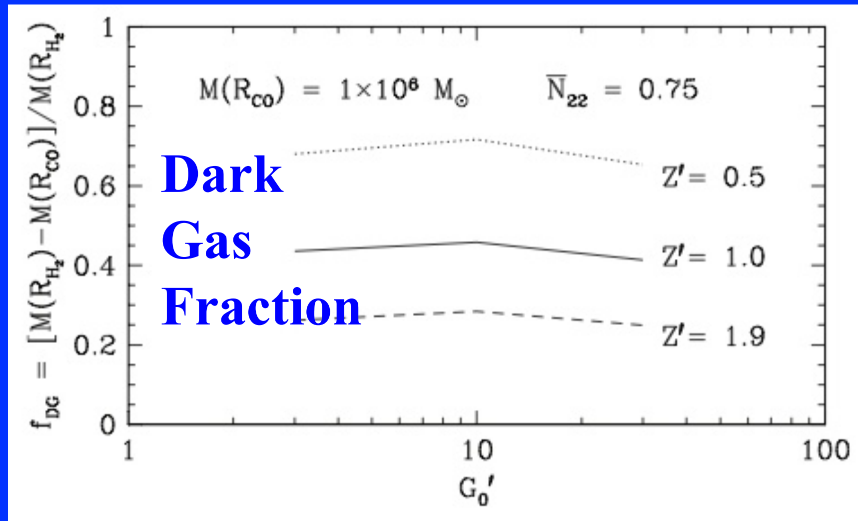
Wolfire, Hollenbach, & McKee 2010

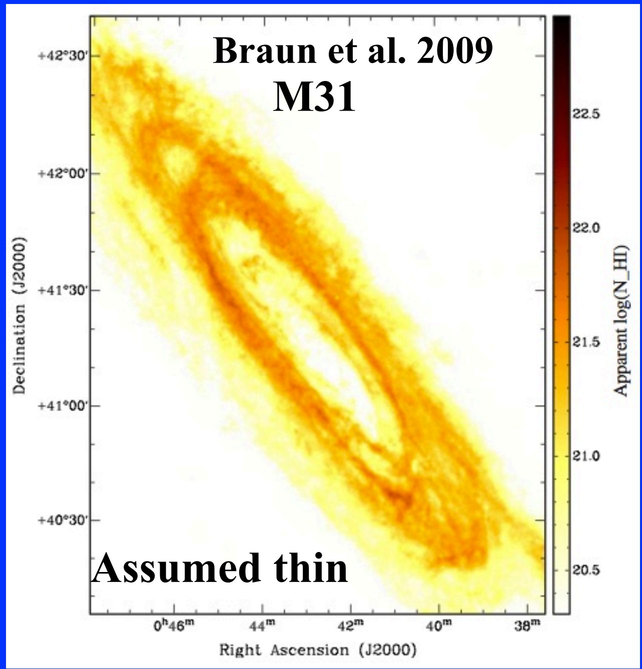
Tielens & Hollenbach 1985
van Dishoeck & Black 1988
Madden et al. 1997
(IC 10 80% PDR with C^+/H_2)

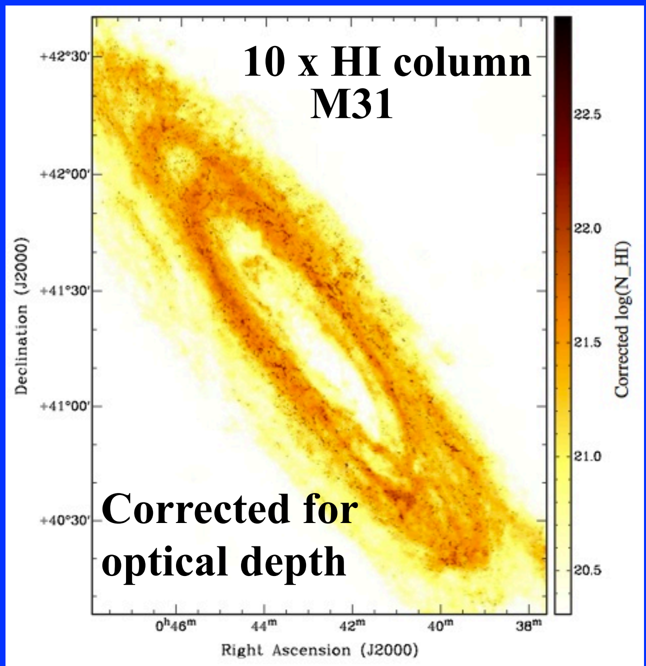
$$f_{DG} = 1 - \exp\left(\frac{-4.0\Delta A_{V,\,DG}}{\bar{A}_V}\right)$$

$$\bar{A}_V \equiv 5.26 Z' \bar{N}_{22}$$









Dark ~~Molecular~~ Gas ?

C^+/H_2 but no CO

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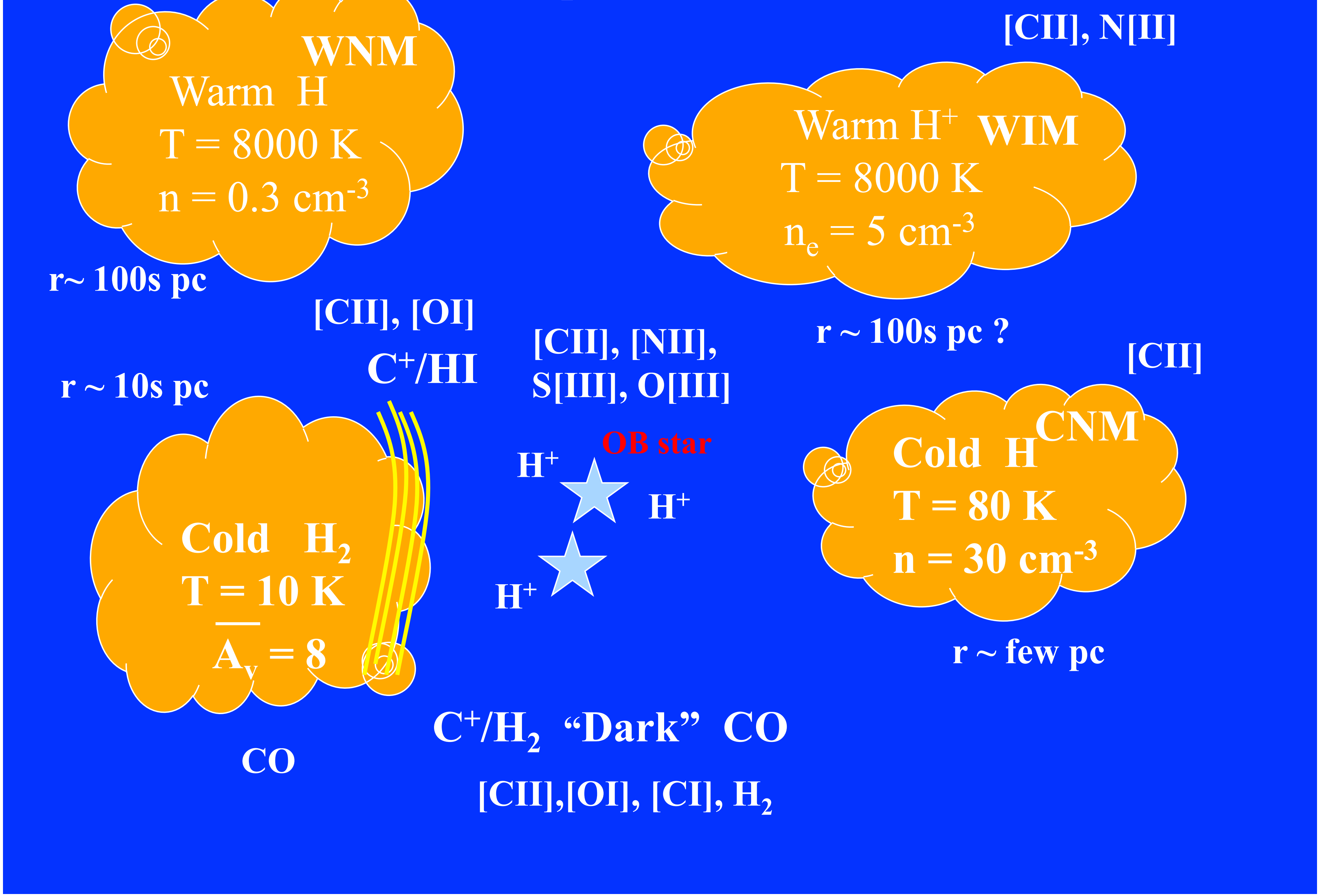
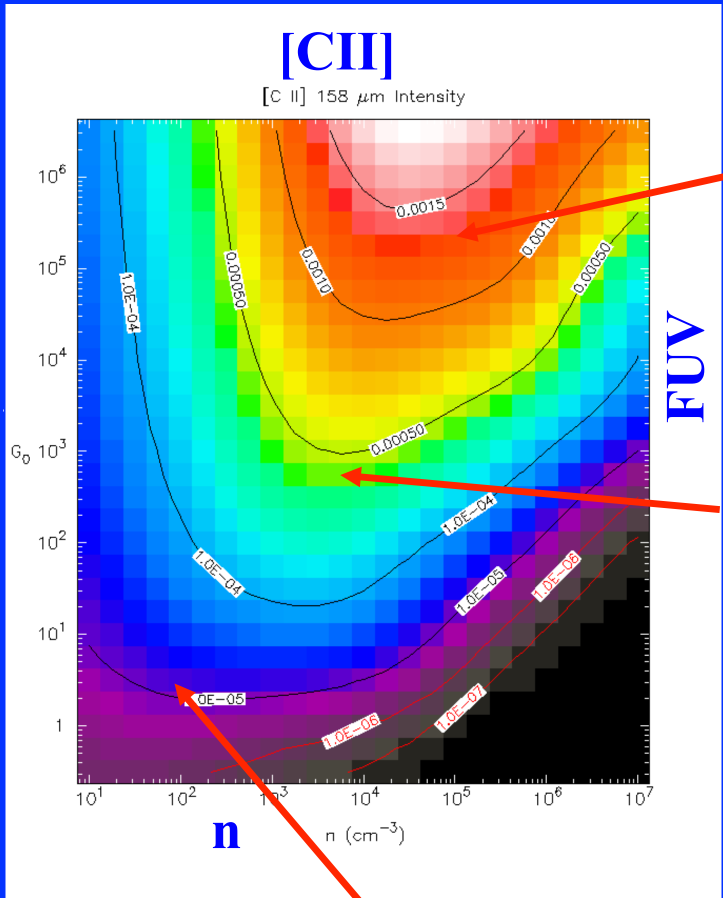
Hydro Models:
FUV penetration:
Glover & Mac Low 2011
Distribution of densities:
Glover & Mac Low 2007
Time dependence: Clark et al 2012

Decomposition of Phases



PDR Emission



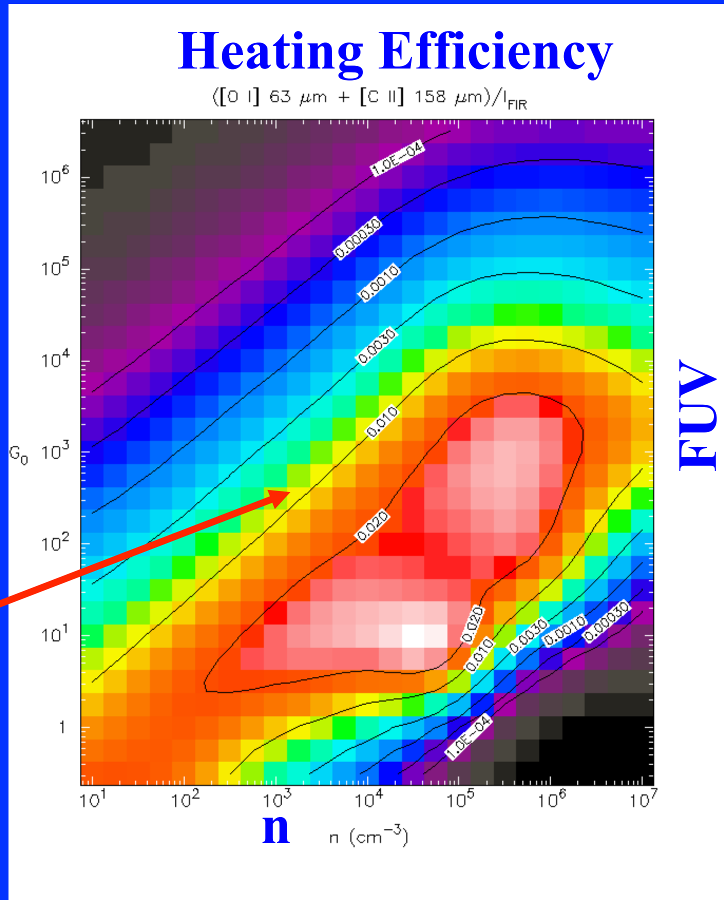
Kaufman et al. 1999

Orion PDR

Classic PDRs

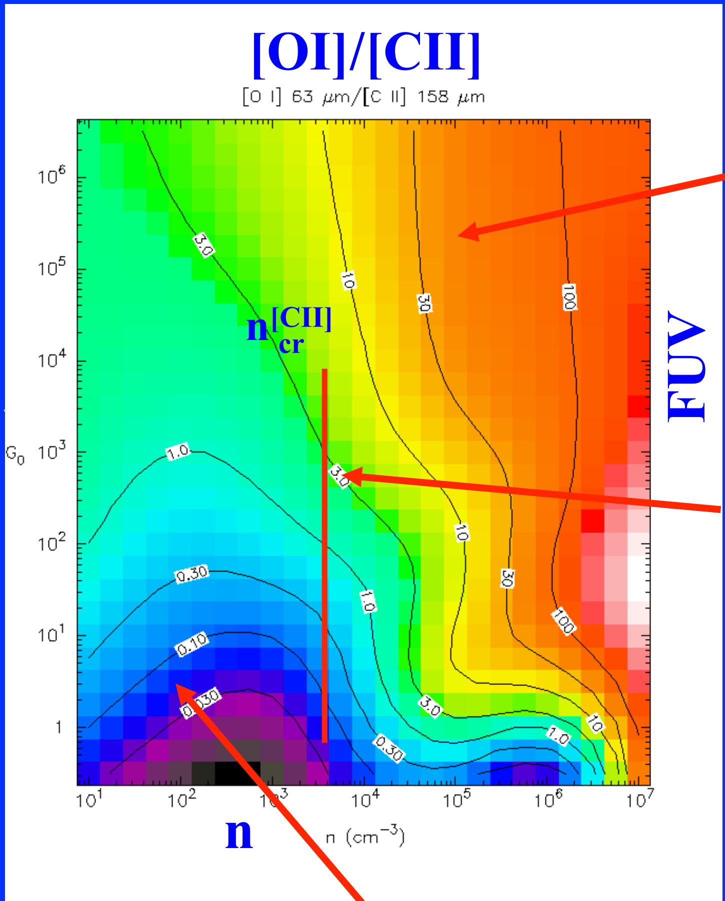
G_0/n = const

Diffuse Gas

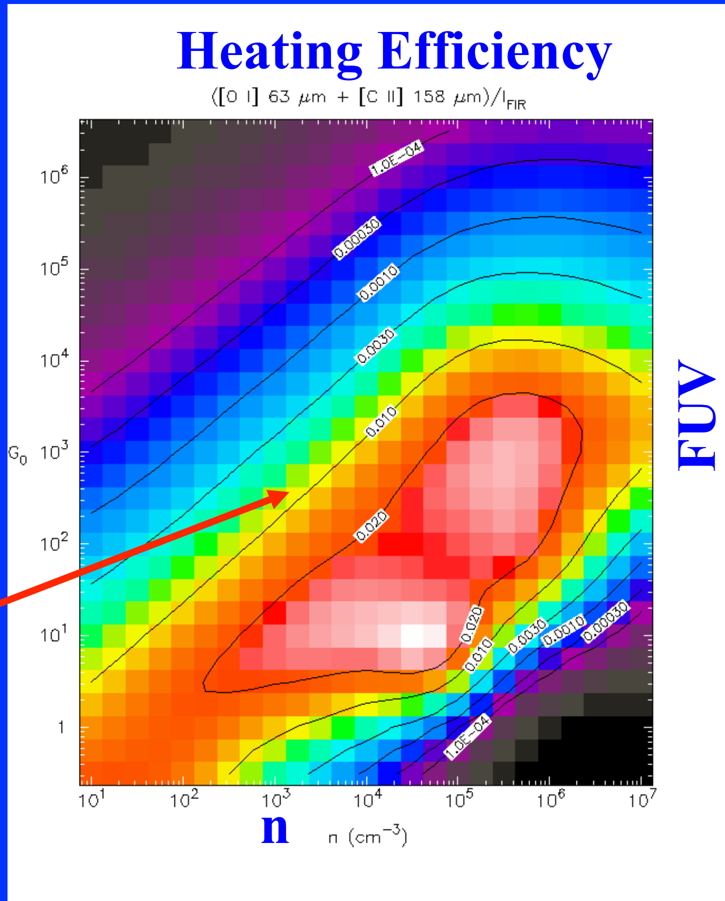


Kaufman et al. 1999

PDR Emission



Kaufman et al. 1999



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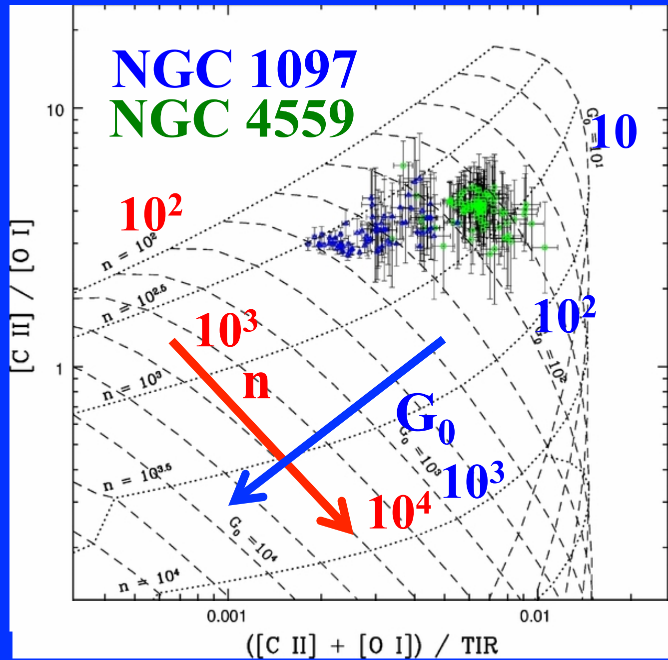
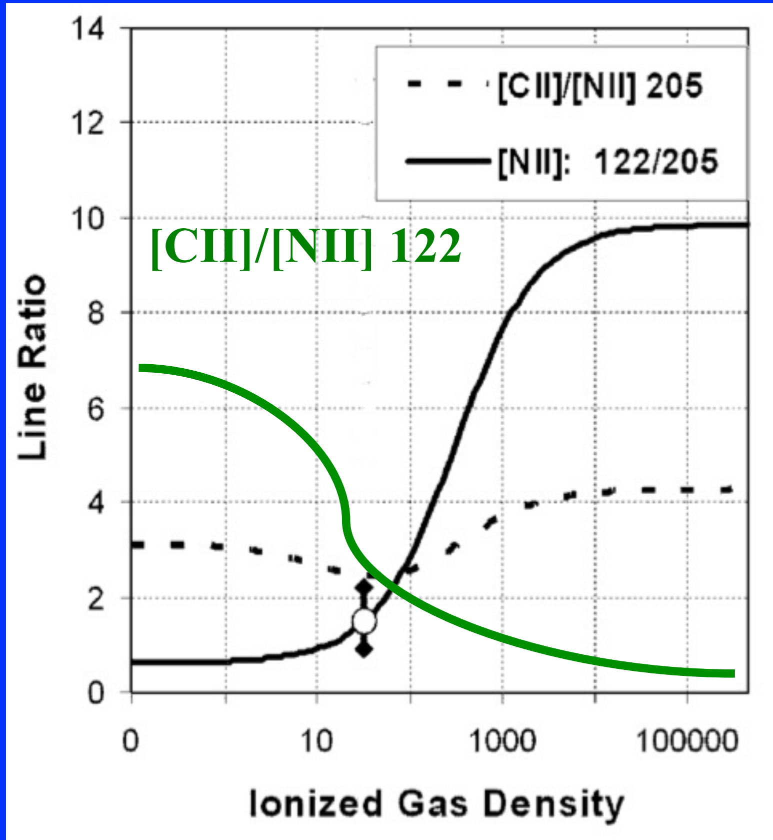
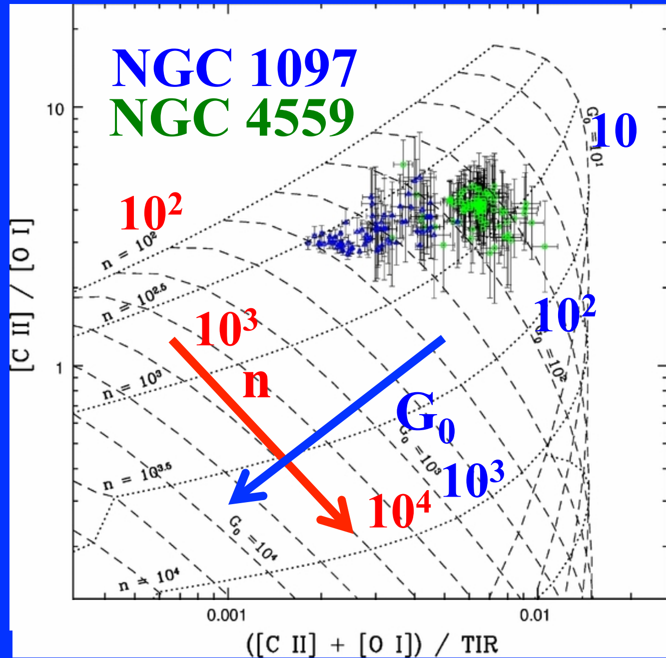


Croxall et al. 2012



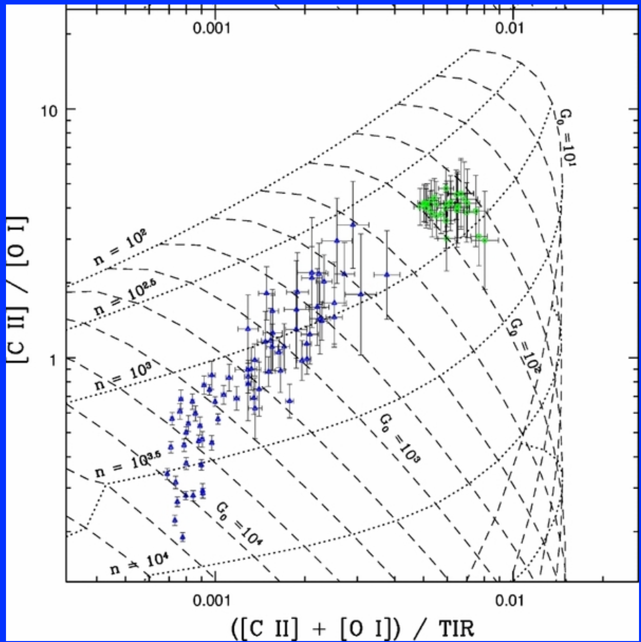
Oberst et al. 2006



Croxall et al. 2012

What n_e to use?

Get n_e from [SIII] 18.7/33.5 for $n_e > 10^2$
or
Pick $n_e = 10$



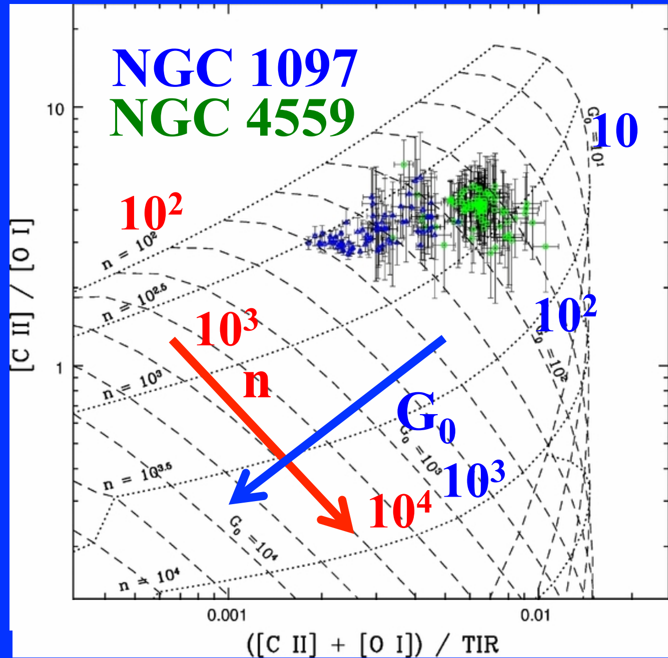
[NII] 122
+ [SIII] 18.7/33.5

Ionized Gas

←

or

[NII] 122
+ $n_e = 10$



Croxall et al. 2012

↘

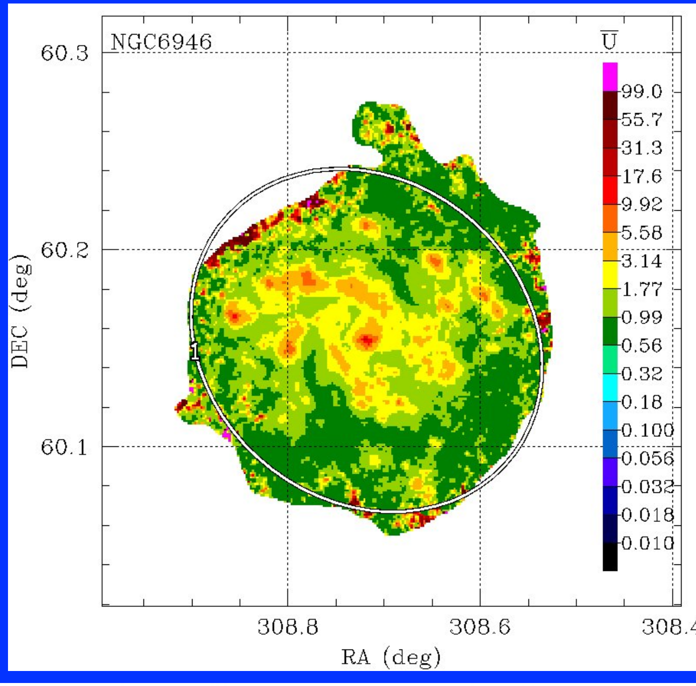
Diffuse neutral emission
Constraints from dust emission

Averge U from dust emission

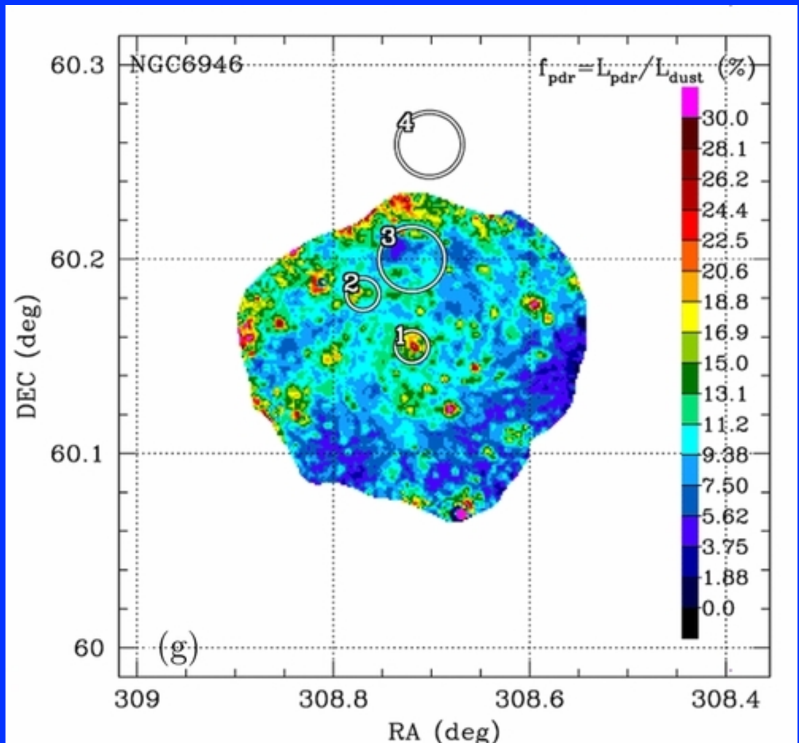
$$dM_{\rm dust} \propto (1-\gamma)U_{\rm min} + \gamma U^{-2}$$

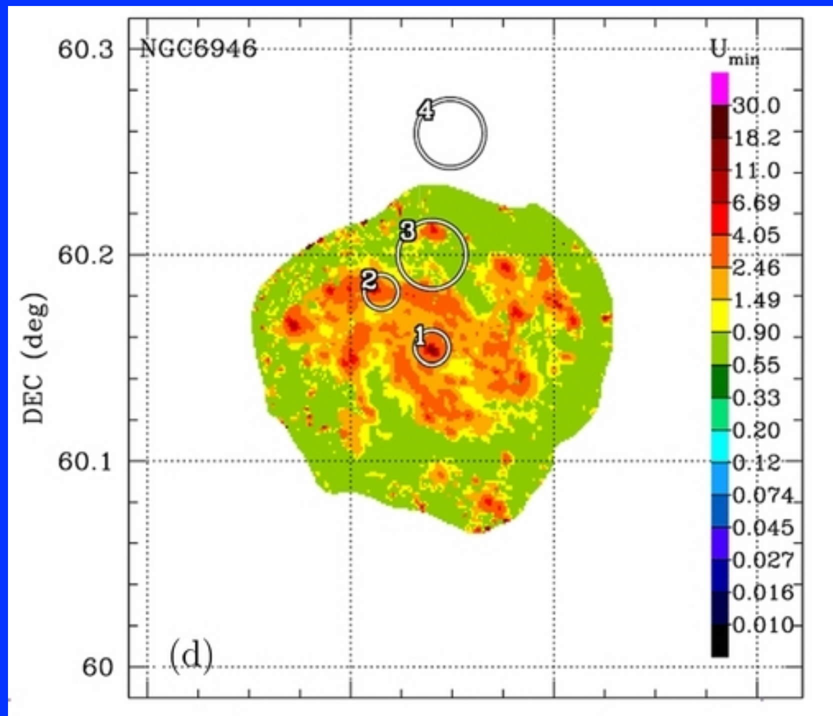
$$L_{\rm PDR} \propto L(U > 100)$$

Draine & Li 2007

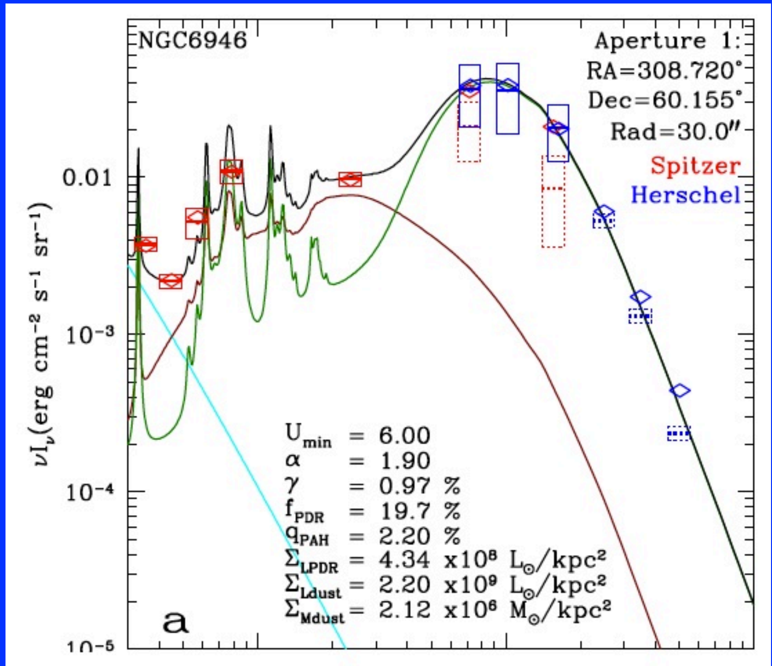


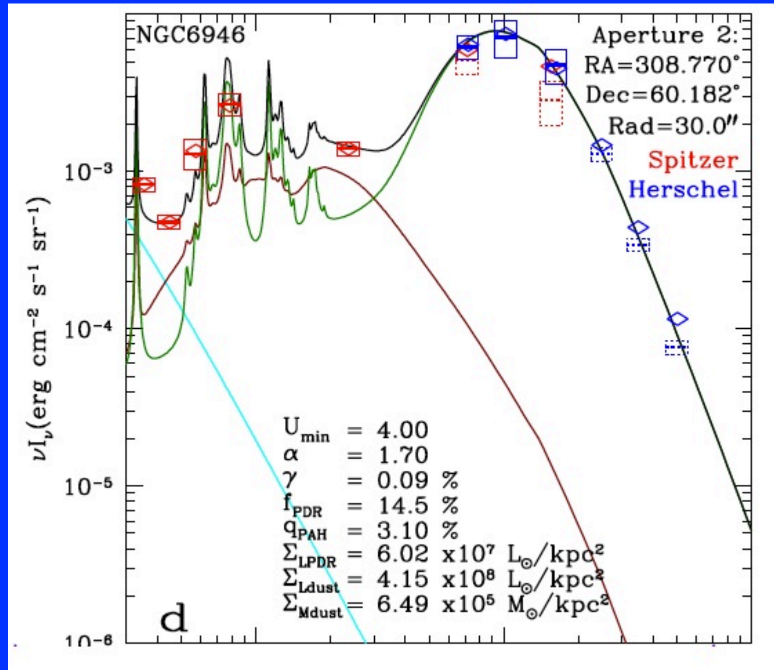
NGC 6946 PACS 160 resolution ~ 165 pc

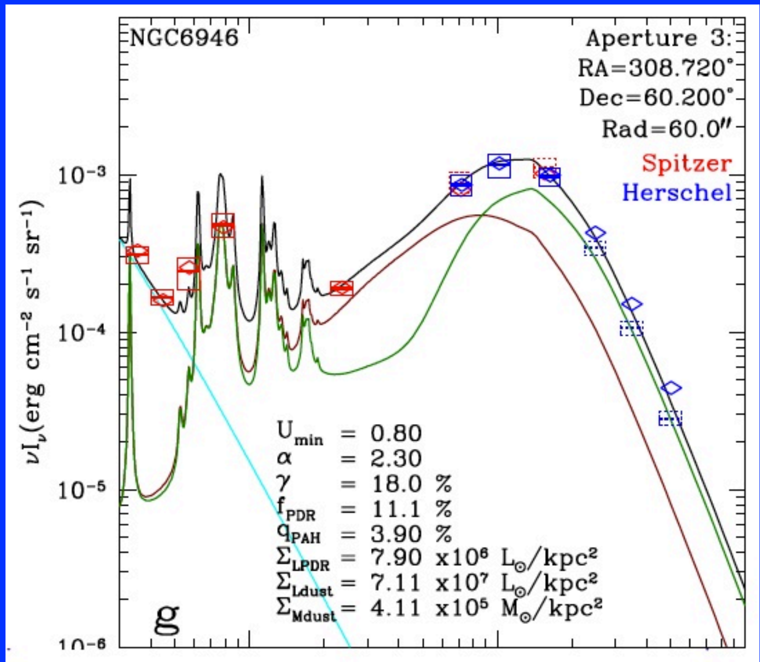




Aniano et al. 2012







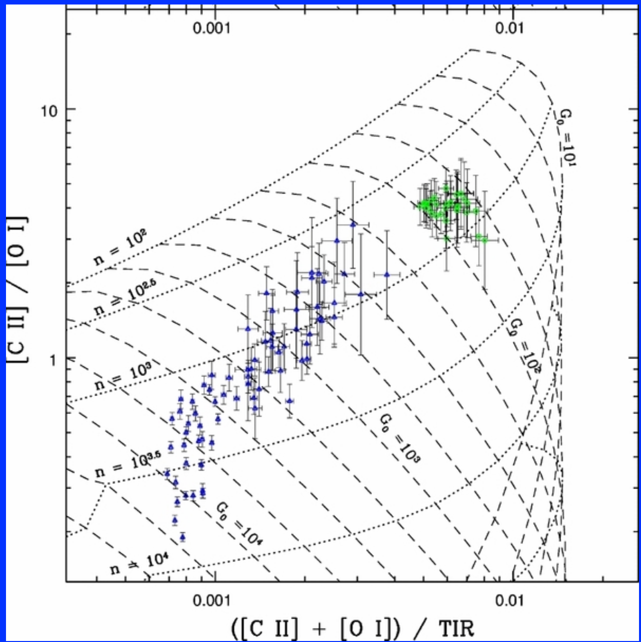
Aniano et al. 2012

Low average U ~ 5, low f_{PDR} < 20%

Diffuse gas + low U on GMCs

Also Cubick et al. 2008, Pineda et al. (2010 , 2013) find U < 100

Wolfire, Hollenbach in prep: average U on GMCs ~10-30

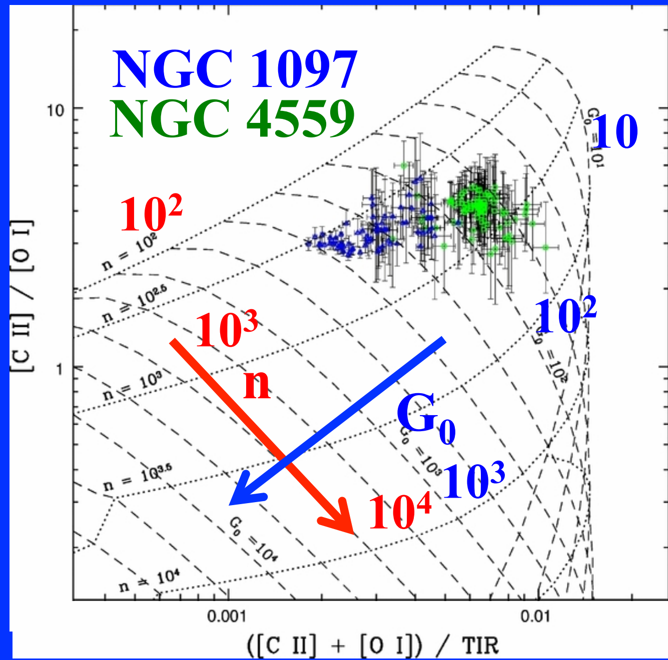


[NII] 122
+ [SIII] 18.7/33.5

Ionized Gas

or

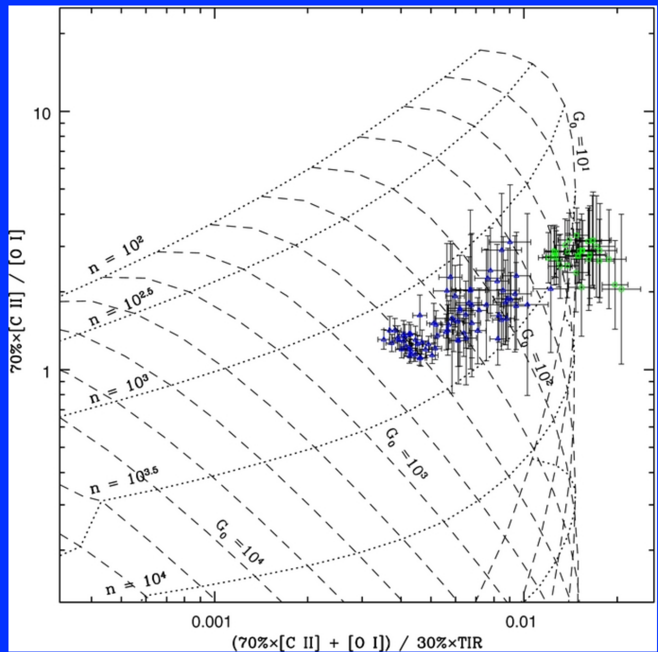
[NII] 122
+ $n_e = 10$



Croxall et al. 2012

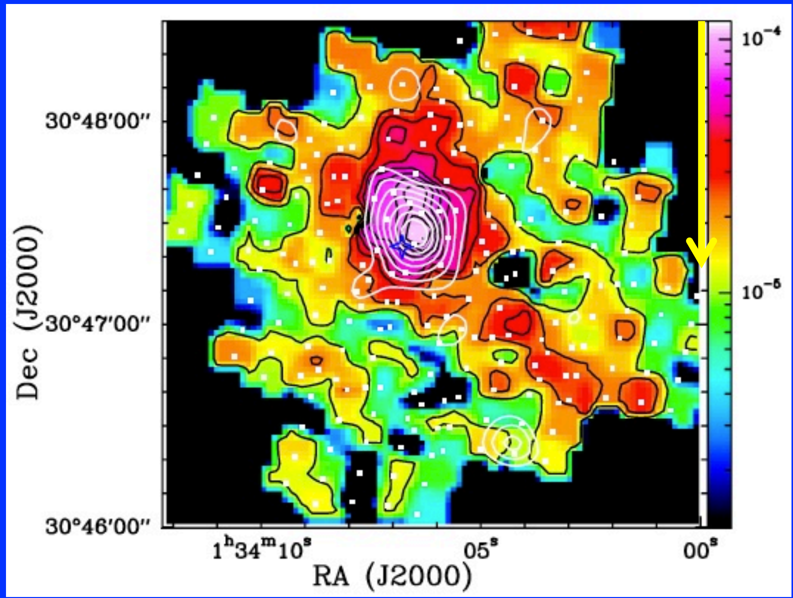
Diffuse Gas

30% of [CII]



[NII] 122
+ $n_e = 100$

PACS [CII] [OI] M33 HII Region

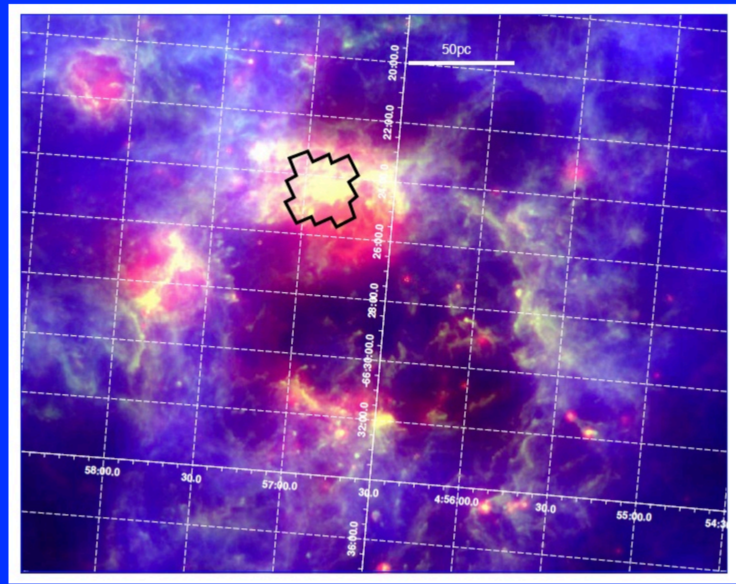


Mookerjea et al. 2011 HerM33es

20-30% [CII] ionised gas

80-70% [CII] neutral PDR

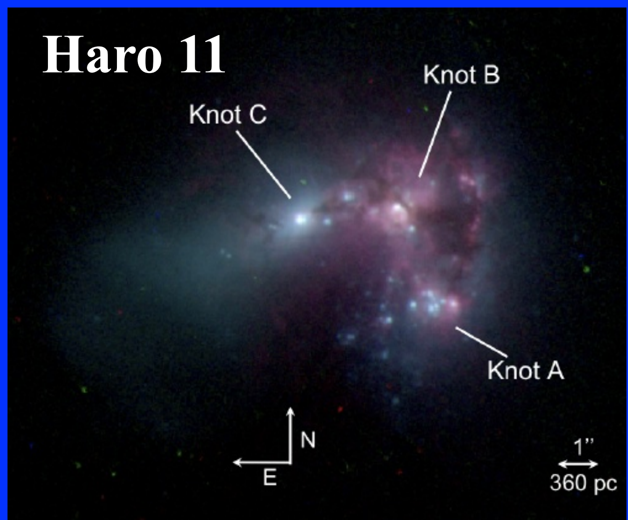
PACS [CII] [OI] LMC-N 11B



Lebouteiller et al. 2012 SHINING

5-15% [CII] diffuse ionised

85-95% [CII] neutral PDR



Cormier et al. 2012

90% [CII] diffuse

10% [CII] neutral PDR

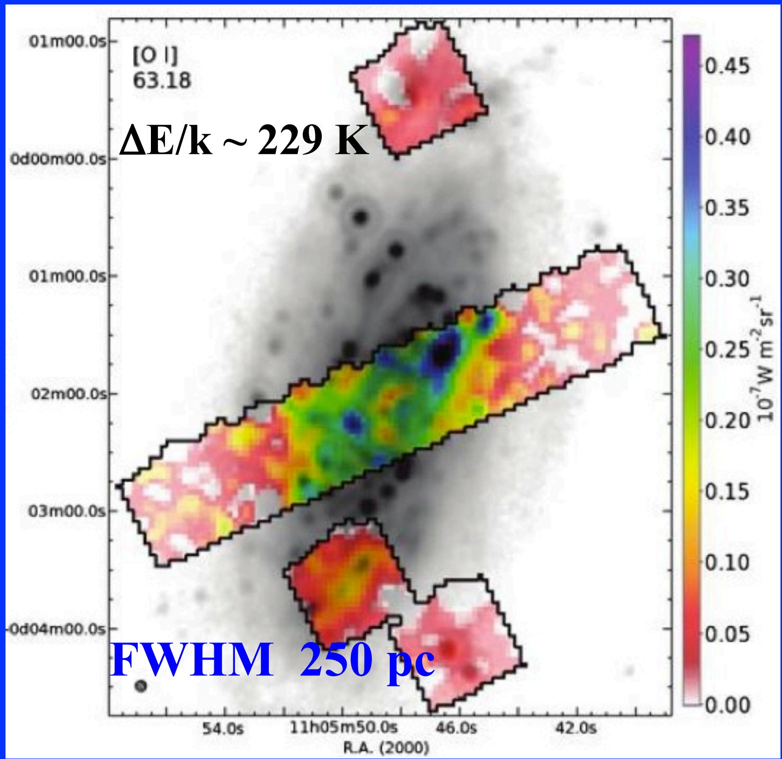
KINGFISH

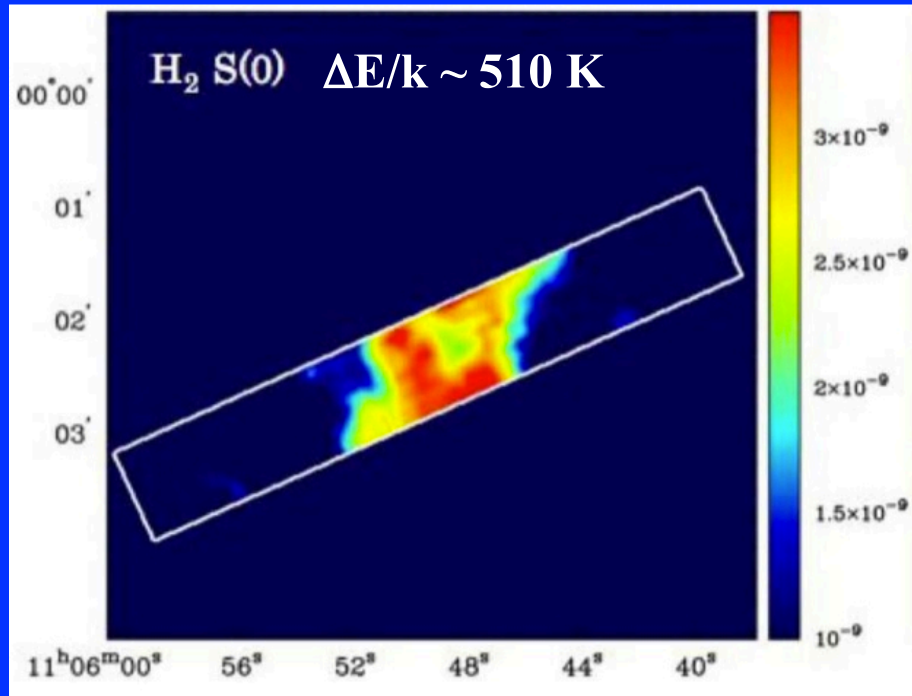
Herschel PACS

NGC 3521

SINGS

Spitzer IRS





Kennicutt et al. 2011

Brunner et al. 2009

Roussel et al. 2007

X-rays ? Meijerink et al. 2007

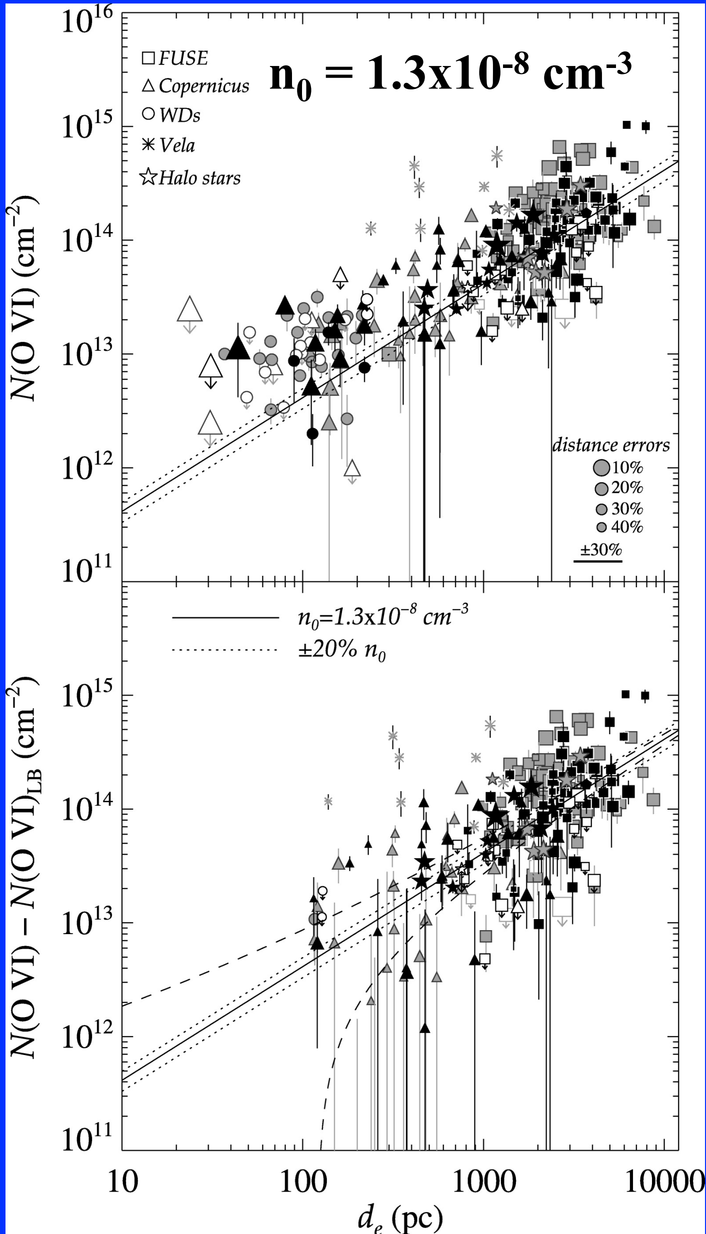
Cosmic Rays ? Meijerink et al. 2011

Shocks ? Appleton et al. 2006

Turbulent Dissipation ? Godard et al. 2009

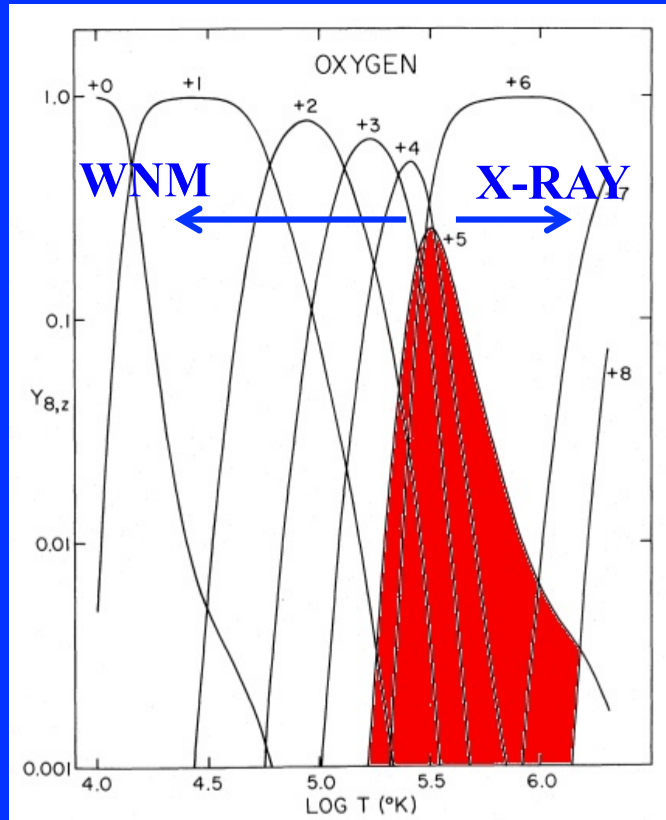
Large scale mechanical energy dissipation ?

Phase Distribution Constraints from OVI



Bowen et al. 2008

N(OVI) from FUV absorption line of OVI

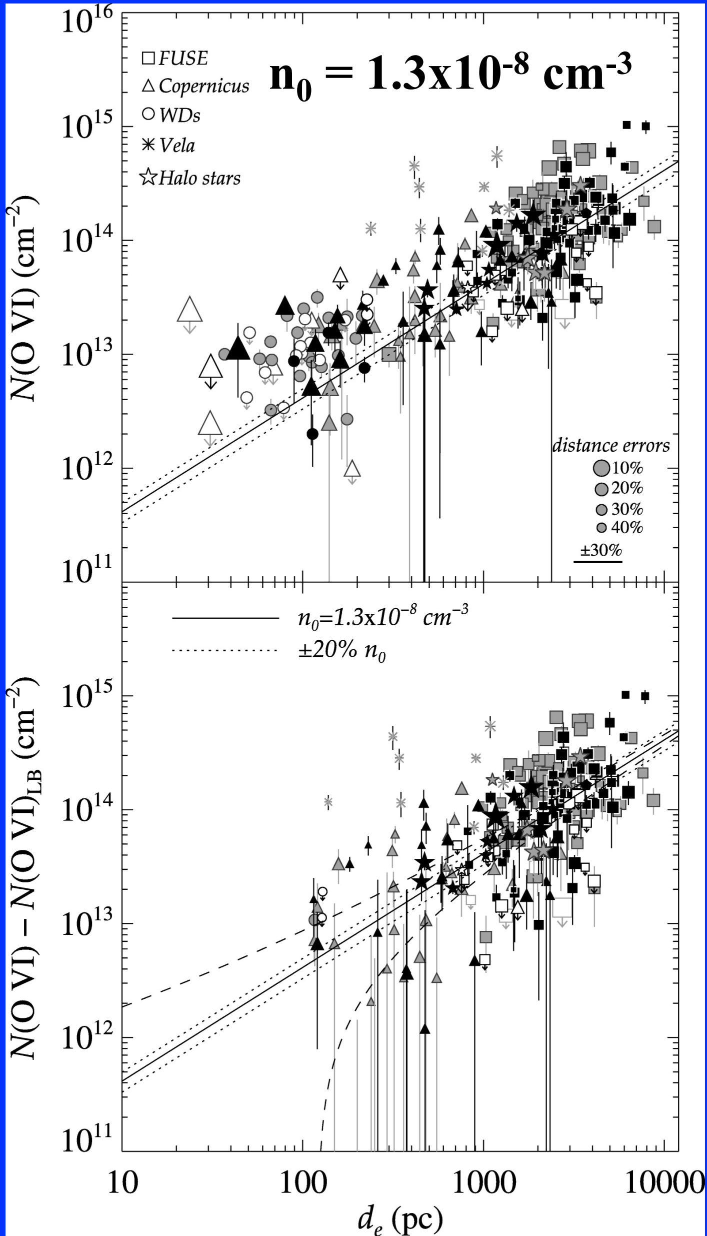


Conductive interfaces

Turbulent mixing layers

de Avillez & Breitschwerdt 2005

Phase Distribution Constraints from OVI



Bowen et al. 2008

N(OVI) from FUV absorption line of OVI

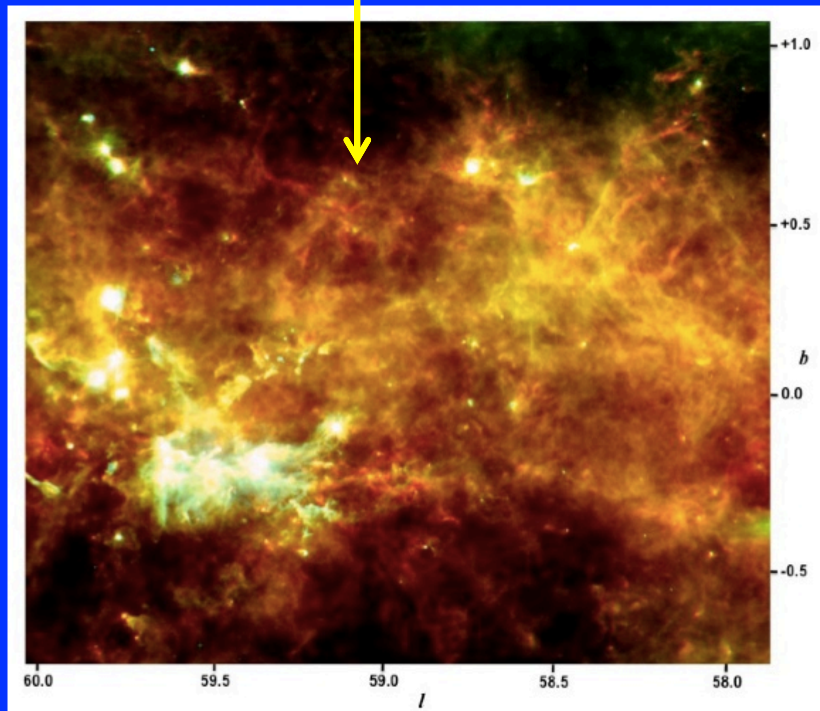
n(OVI) only few 10^{-8} cm^{-3}

D. Cox numerous

MO too much OVI

Slavin & Cox clouds in WNM reduces OVI

Reality!



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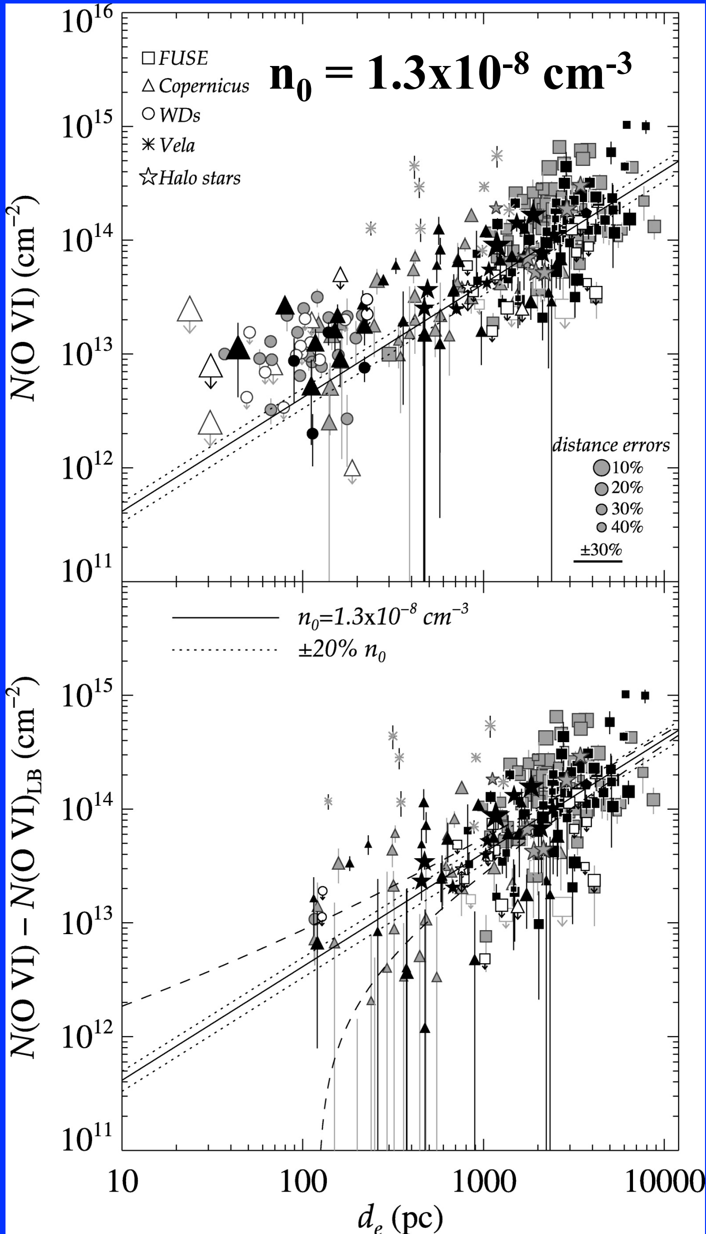

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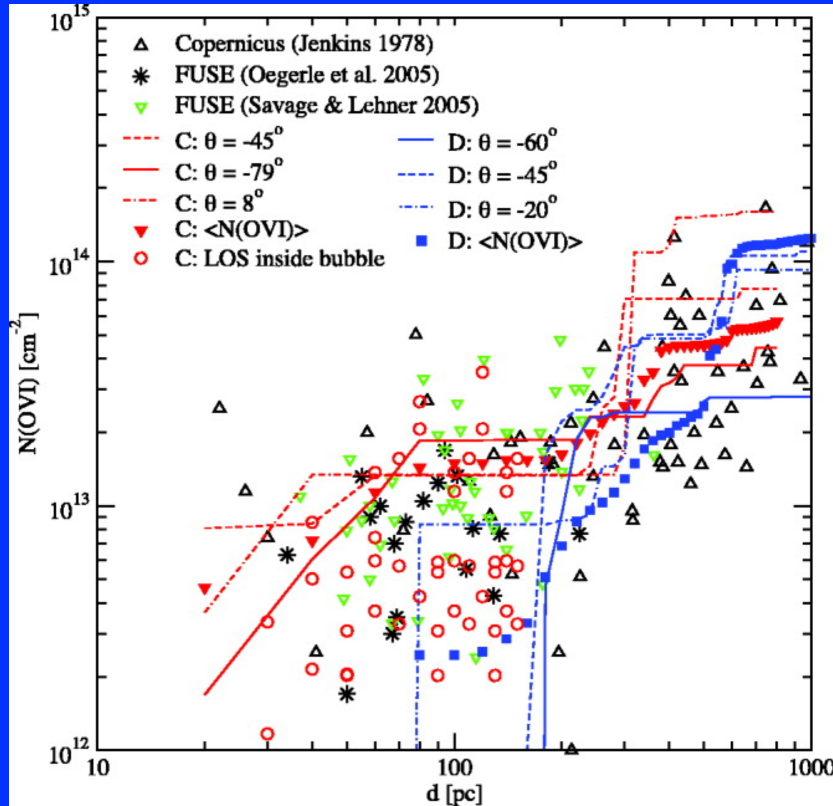

de Avillez & Breitschwerdt 2005

Conclusions

1.)CNM pressure distribution width set by turbulence but median set by two-phase pressure.

2.)Tenatively: the mass fraction of in-plane thermally unstable gas is not very high. I am waiting for better statistics.

3.)The mass fraction of out-of-plane thermally unstable gas IS high

4.)Self-regulating cycle (pressure, star formation, phase transitions) maintains the two-phase pressure in the midplane

5.)Dark gas. How do models compare with observations (at low Z). Could it be substaintially HI and not H_2? Do hydro models produce more DG?

6.) Ample evidence for small scale mechanical heating/turbulent dissipation. Can this dominate at large scale in diffuse gas?

Conclusions

7.) [CII] mainly comes from moderate n and moderate to low G_0 PDRs plus some neutral diffuse gas (mainly in outer galaxy).

8.)WIM/HII contribution to [CII] is uncertain ~30%

9.)OVI constraints. Must not overproduce OVI. Likely comes from turbulent mixing regions between HIM/CNM/WNM